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Extending growing period is limited to offsetting negative effects of climate changes on maize yield in the North China Plain

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ABSTRACT

Climate changes in temperature, solar radiation, and precipitation potentially interrupt progressive improvement in crop yield. Genetic and agronomic strategies to adapt climate changes were proposed in previous studies, but were rarely evaluated. In this study, meteorological data from 1954 to 2014 at one representative station in the North China Plain (NCP), model simulation of Hybrid-Maize, and a field experiment were combined together to detect climate change impacts on maize yield and to assess the adaptive effects of cultivars. Three maize cultivars with contrasting lengths of growing period were grown at three specific plant densities. Cultivar with a long growing period (LG) was grown at 67500 (optimal density), 82500, and 97500 plant ha^{-1}, medium-growing (MG) cultivar at 82500 (optimal), 97500, and 112500 plant ha^{-1}, and short-growing (SG) cultivar at 97500 (optimal), 112500, and 124500 plant ha^{-1}. During the past six decades, temperature increased and solar radiation decreased significantly in the total, vegetative, and reproductive growing periods of maize in the NCP with a slight decline in precipitation. These climate changes significantly reduced yield at a rate of 30.8, 31.3, and 25.0 kg ha^{-1} yr^{-1}, respectively, for SG, MG, and LG maize cultivars. Decline in growing degree days (GDD) use efficiency of LG cultivar with changing climate was one-fold slower than that of SG and MG cultivars. MG maize cultivar was estimated to produce the highest grain yield in NCP owing to its relatively long growing period and high tolerance of plant density. LG maize cultivar has a larger potential to adapt changing climate, but has a larger difficulty in improving yield because of lower tolerance of high plant density. Improvement of plant architecture in space and in time is expected to resolve the conflict between adapting climate changes and tolerating high plant density in maize.

1. Introduction

Climate changes retard the increase in global yield of many crops such as maize (Butler and Huybers, 2013), wheat (Hochman et al., 2017), and rice (Zhang et al., 2013) in the past several decades. The North China Plain (NCP), one of the most important agricultural production areas in China, is being confronted with an increasing challenge in enhancing crop yield due to the climate changes (Sun et al., 2007; Chen et al., 2010; Liu et al., 2010). Maize crop in NCP contributed more than 30% of China maize production, influencing food security for the millions of people in China and beyond (Tao et al., 2006; Wang et al., 2012).

Increased temperature and decreased solar radiation were estimated to reduce maize yield by 15–30% in some regions of NCP in 1981–2009, and the decreased precipitation likely further reduced maize yield by 3% (Xiao and Tao, 2016). The yield decline is attributed to the changes of maize phenology in relation to climate changes (Estrella et al., 2007; Xiao et al., 2016). Warming climate can advance flowering and maturity of maize and consequently shorten growing period (Tao et al., 2014). The shortened growing period can further reduce solar radiation accumulated in the maize season. Solar radiation deficit can reduce internode length in the vegetative growing period of maize (Fournier and Andrieu, 2000), and cause kernel losses at silking stage (Setter et al., 2001). Therefore, the decrease in the accumulated solar radiation is supposed to have more negative effects (Chen et al., 2013a; Xiao and Tao, 2016).

Adjustment of sowing time and cultivar shift were considered important mitigation strategies for climate changes (Howden et al., 2007; Liu et al., 2009; Deryng et al., 2011; Liu et al., 2013). Sowing earlier can partly offset the negative effects of climate change on maize yield (Rose et al., 2016). In the northeast China, per day extension of growing period by advancing sowing can increase maize yield by up to 4% in 1981–2007 (Liu et al., 2013; Zhao et al., 2015). Similar evidences were also found in NCP (Tao et al., 2014; Xiao and Tao, 2016), but the effects

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of early sowing is supposed to be limited in this region because of the double cropping system of winter wheat and summer maize. Growing season of summer maize is restricted in a specific period ranging from June to early October in NCP (Sun et al., 2007). Sowing maize earlier would advance harvest of wheat, thus influencing wheat maturity and yield.

Cultivars with a longer growing period can extend the warming-shortened growing period of maize, increasing the utilization of potential thermal time as well as improving grain yield (Sacks and Kucharik, 2011; Tao et al., 2014; Zhao et al., 2015). Results of Tao et al. (2014) indicated that growing period of maize was significantly prolonged at around 40 out of 112 experimental stations across China in 1981–2009. Growing season of maize is extending in some regions where chilling stress is alleviated as a result of increased thermal time such as Central Europe (Rose et al., 2016) and Northeast China (Zhao et al., 2015). With these in mind, maize cultivars with a longer growing period would be favored in the context of warming climate.

In addition, increasing plant density is an important strategy to increase maize yield (Tokatlidis and Koutroubas, 2004; Testa et al., 2016) by changing plant architecture (Duvick, 2005; Lee and Tollenaar, 2007; Hammer et al., 2009). Plant phenotype is assumed to be related to plant growing period (Sultan, 2000), indicating that plant density tolerance is associated with growing period to some extent. Evidences for adapting changing climate are, however, particularly lacking when growing period and plant density tolerance of maize are both taken into account.

In view of the various factors considered, a field experiment, Hybrid-Maize Model simulation, and meteorological data from 1954 to 2014 were combined in this study. The Hybrid-Maize Model is able to estimate the potential yield of maize, climatic impacts on maize yield (Chen et al., 2013b), and varietal effects on offsetting climate change (Meng et al., 2016). The objectives of this study were (i) to detect responses of three maize cultivars with contrasting lengths of growing period (also referred to as contrasting plant sizes) to climate changes in the North China Plain in the past six decades, and (ii) to analyze the mechanisms to further improve maize yield in the context of changing climate.

2. Materials and methods

2.1. Study site and climate

The study was conducted in the Wuqiao experimental station (37°41′02″N, 116°37′23″E) of China Agricultural University in 2007, east part of North China Plain (NCP). In this site, soils were loams with soil pH of approximately 8.0. Soil of 0–20 cm depth contained 11.1 mg kg^{-1} organic matter, 0.7 mg kg^{-1} total N, 23.8 mg kg^{-1} available phosphorus (Olsen-P) and 146.7 mg kg^{-1} ammonium acetate extractable potassium (K). Meteorological data from 1954 to 2014 for Botou (38°05′N, 116°33′E, 50 km from Wuqiao) were obtained from the China Meteorological Data Sharing Service System (http://www.cdc.nmic.cn). Meteorological data collected from Wuqiao experimental station was not complete for Hybrid-Model simulation, and was not recorded in the China Meteorological Data Sharing Service System. The downloaded climate data include daily solar radiation, precipitation, relative humidity of the air, wind speed, and daily mean, maximum and minimum temperatures. The parameter growing degree days in the whole growing season (tGDD), vegetative (vGDD) and reproductive growing seasons (rGDD) of summer maize were calculated using a base temperature of 10 °C.

2.1.1. Experimental design

The field trial used three maize cultivars with contrasting growing periods, and each of them were planted in three densities and in three replicates. Maize hybrids CF008 has a short growing period (SG), ZD958 has a medium growing period (MG), and JH5 has a long growing period (LG). Plant densities of 97500, 112500, and 127500 plants ha^{-1} were used for CF008; 82500, 97500, and 112500 plants ha^{-1} for ZD958; and 67500, 82500, and 97500 plants ha^{-1} for JH5.

The plot size was 10 × 6 m (10 m long and 6 m wide) with a row spacing of 0.6 m. All the plots were provided with 36 kg ha^{-1} N (78 kg ha^{-1} urea), 105 kg ha^{-1} P_2O_5, 113 kg ha^{-1} K_2O, and 15 kg ha^{-1} $ZnSO_4$ before sowing; Extra 144 kg ha^{-1} N (313 kg ha^{-1} urea) in each plot was applied at 6-leaf stage (V6). Maize seeds of three cultivars were sown on the same day (June 16) in 2007, and were harvested on different days, depending on the maturity degrees of varieties (September 23 for CF008, September 25 for ZD958, and October 2 for JH5). To assure the expected plant densities, three seeds were sown per pit, and only one seedling was thinned left at the 3-leaf stage. Weeds, pests, diseases were well controlled in the whole growing season. To avoid drought stress, the field was irrigated shortly after sowing with 75 mm ha^{-1}.

2.1.2. Dry matter accumulation, translocation, and yield measurement

At 8-leaf, 12-leaf, silking, mid grain filling (about 25 days after silking) stage, and immediately before harvest, above-ground parts of three randomly selected plants were collected, from which leaves, stems, and/or grains were separated. The fresh samples were oven-dried at a temperature of 80 °C for 48 h, and were weighed to measure whole-plant dry matter (DM) accumulation (g $plant^{-1}$) above ground as follows,

DM accumulation per unit area (kg ha^{-1}) = whole-plant DM accumulation × plant density per unit area/1000.

To measure the potential grain filling rate, the kernels at the central position of five cobs sampled at each plot were dried, weighed, and were counted at 25 and 40 days after silking (DAS).

The potential grain filling rate (g $kernel^{-1}$ day^{-1}) = (kernel weight/kernel number at 25 DAS − kernel weight/kernel number at 40 DAS)/(40 − 25).

Harvest was carried out when black layer was visible in 50% of the ears. At the central of each plot where no plants were sampled, all the ears in four adjacent rows 5 m long were harvested to determine grain yield and yield components. The grains were oven-dried at 80 °C to determine grain water content, and then was adjusted to 14% moisture. Kernel number per ear and 1000-kernel weight was measured.

DM translocation (DMT) was calculated as (Rajcan and Tollenaar, 1999)

DMT (kg ha^{-1}) = (DM at silking − DM in the stover at maturity) per plant × plant density/1000

The contribution of DMT to grain yield was as calculated as

DMT (%) = (DM at silking − DM in the stover at maturity)/(grain yield) × 100

Harvest index (HI, %) = whole plant grain yield at maturity/whole plant DW at maturity × 100

The calculation of potential climatic resource use efficiency (CRUE) was as follows

Potential CRUE in the whole growing season = potential yield/climatic variables during the whole growing season (such as total solar radiation, growing degree days, and precipitation). The potential yield was estimated by the Hybrid-Maize Model.

Potential CRUE in vegetative phase = potential yield/climatic variables during the vegetative phase (such as solar radiation, growing degree days, and precipitation from sowing to silking).

Potential CRUE in reproductive phase = potential yield/climatic variables during reproductive phase (such as solar radiation, growing degree days, and precipitation from silking to harvest).

2.1.3. Morphological and physiological parameters

Plant height and ear height of 10 plants in each plot were measured at silking stage. Leaf area was measured at siking and mid grain filling stages of three carefully selected plants in each plot.

Leaf area = Σ (leaf length × maximum leaf width) × 0.75 (Montgomery, 1991).

Leaf area index LAI = leaf area/soil area unit.

LAI at silking was considered as the maximum LAI.

To compare the ability of green leaf persistence of maize hybrids, a curvilinear equation $y= ae^{b-cx}/(1 + e^{b-cx})$ was used to simulate the relative green leaf area (RGLA) (Liu et al., 2009), where y is RGLA, x the days after silking, a the initial RGLA (set to 1 in this study for all the cultivars), b the scale parameter, and c the shape parameter. Parameters b and c were determined by LAI at siking and mid grain filling stages.

To detect light extinction coefficient (k), transmitted photosynthetically active radiation (TPAR) was measured below green leaves in each plot (four replicates) at silking stage, between 11:00–14:00 on a clear day with a 1-m line quantum sensor (LI-191SA, LI-COR, Lincoln, NE). The corresponding incoming photosynthetically active radiation (IPAR) was measured above the population canopy. According to the formula of Maddonni et al. (2001) and Lizaso et al. (2003), k was calculated as

$$k = \frac{-\ln\left(\frac{TPAR}{IPAR}\right)}{LAI},$$

and light interception (%) was

$$Light\ \ interception = \left(1 - \frac{TPAR}{IPAR}\right) \times 100$$

At silking stage and 30 days after silking (mid grain filling stage), the leaf net photosynthetic rate (*Pn*) of three leaves at ear layer (the 1st leaf below the ear, ear leaf, and the 1st leaf above the ear) of three cultivars were measured, using portable photosynthesis system (Li6400; LI-COR, Lincoln, NE, USA). Three plants in each plot were measured between 9:00–15:00.

2.1.4. Crop modelling and simulation

The Hybrid-Maize Model combined strengths of growth and development functions in CERES-Maize (Kiniry et al., 1997) and of mechanistic formulas of photosynthesis and respiration in INTERCOM (Kropff and van Laar, 1993) and WOFOST (Van Diepen et al., 1989), and its specific features, e.g. integration of growing degree days (GDD), gross assimilation, and growth or maintenance respiration (Yang et al., 2004). Its application on simulation of maize grain yield at harvest was widely acceptable, and the accuracy was reliable at different regions (Yang et al., 2004, 2006; Chen et al., 2013b). In this model, the inputs comprise of general inputs (such as historical weather data, sowing date, cultivar maturity, and plant density), water condition (rainfed or irrigated), and soil properties. The key parameters for crop management, crop growth, respiration and photosynthesis, and soil are allowed to be modified based on field observations.

In the present study, soil parameters were default values in the model. Weather variables consisted of solar radiation, daily air maximum and minimum temperatures, relative humidity, rainfall, and reference evapotranspiration were derived from China Meteorological Data Sharing Service System (http://www.cdc.nmic.cn). The crop parameters for simulation of potential yield were adjusted based on field observation in 2007 (Table 1). Irrigation was conducted when drought stress occurred in the experimental region, so estimate irrigation of water requirement was selected in the simulation. Sowing date was set to June 16 with a sowing depth of 4 cm.

2.2. Statistical analysis

Trends in climatic variables (solar radiation, GDD, and precipitation), potential yield and climatic resource use efficiency from 1954 to 2014 were established using linear regression analysis. Student's *t*-test was used to evaluate the slop of trends at $P < 0.05$ or $P < 0.01$. Field observations (LAI, light interception, leaf net photosynthesis, DW accumulation and translocation, and yield and yield components) were analyzed by analysis of variance using SAS 9.3 (SAS Institute, Carey, NC, USA). The least significant difference (LSD) test was used to compare the difference. Correlation between observed yield and simulated yield was calculated with proc corr of SAS 9.3.

3. Results

3.1. Climate change from 1954 to 2014

In the past six decades, the growing degree days in the whole growing season (tGDD), vegetation phase (vGDD, pre-silking), and reproductive phase (rGDD, post-silking) of summer maize increased at a rate of 1.45, 0.69, and 0.76 °C yr^{-1}, respectively (Fig. 1a). Conversely, the solar radiation accumulated in the above three growing periods decreased significantly (Fig. 1b); and precipitation decreased by 1.75, 1.0, and 0.75 mm year^{-1}, but the decreases were not significant at $P < 0.05$ (Fig. 2). The highest precipitation in maize growing season was 893 mm that occurred in 1964, and the lowest precipitation was 158 mm in 1957 with a mean of 449 mm over 60 years.

3.2. Impacts of climate change and growing period on potential yield of maize

Simulated potential yield of three maize cultivars was closely correlated with observed yield at harvest in 2007 with $R^2 = 0.94$ (Fig. 3), indicating Hybrid-Maize model was suitable for maize yield simulation under this experimental conditions.

The potential yields of three maize cultivars decreased significantly with time (Fig. 4). And the decline trends of cultivar CF008, ZD958, and JH5 were 30.8 (Fig. 4a), 34.7 (Fig. 4b), and 26.6 kg ha^{-1} yr^{-1} (Fig. 4c), respectively. On average over the past 60 years, cultivar ZD958 produced the highest potential yield of 12062 kg ha^{-1} at the optimal density, compared to 10767 kg ha^{-1} of cultivar JH5 and 10430 kg ha^{-1} of cultivar CF008.

3.3. Climatic resource use efficiency

The growing period from sowing to maturity averaged 107 days in the past 60 years for cultivar CF008, and 113 days and 119 days for cultivars ZD958 and JH5, respectively (Table 2). The total growing period of CF008, ZD958, and JH5 decreased with time at an annual rate of 1.9, 2.9, and 3.9 day decade^{-1}. And the decrease was significant in both reproductive and total growing periods for ZD958 and JH5.

The solar use efficiency (potential yield/solar) of all the cultivars used increased with time, but the GDD use efficiency (potential yield/GDD) decreased in the past 60 years (Table 2). MG cultivar ZD958 had the highest climatic resource use efficiency in solar and GDD as compared with CF008 and JH5. The solar and GDD use efficiency between CF008 and JH5 were very close.

3.4. Mechanism of yield production of maize hybrids at the optimal plant density

At the optimal plant density, the maximum LAI of cultivar ZD958 was significantly greater than that of cultivars CF008 and JH5 (Fig. 5a). The relative green leaf area (RGLA) of JH5 decreased much slower with time than that of ZD958, and CF008 had the fastest decline in RGLA (Fig. 5b).

Light interception rate (%) at the population bottom increased with time and reached the highest level at approximately 60–85 days after sowing (DAS) of three maize cultivars (Fig. 6). Cultivar JH5 needed

Table 1
Crop parameters of three maize hybrids at different plant densities used as inputs for Hybrid-Maize Model, based on the field observation in 2007.

Cultivar	Density (10^4 plant ha^{-1})	Potential kernel number (plant^{-1})	Potential grain-filling (mg kernel^{-1} d^{-1})	Light extinction (k)	Dry matter translocation efficiency (g g^{-1})	Relative leaf area index at maturity (m^2 m^{-2})	Total GDD (°C)	Pre-silking DDG (°C)
CF008	9.75	362	10.1	0.50	0.26	0.92	1623	848
	11.25	350	9.6	0.55	0.15	0.89	1623	848
	12.45	310	10.3	0.60	0.16	0.97	1623	830
ZD958	8.25	471	9.0	0.55	0.23	0.87	1663	858
	9.75	375	9.4	0.66	0.19	0.92	1663	885
	11.25	357	8.2	0.69	0.18	0.93	1663	858
JH5	6.75	526	7.8	0.40	0.21	0.62	1697	921
	8.25	403	8.1	0.68	0.19	0.68	1685	921
	9.75	355	8.5	0.75	0.19	0.67	1685	921

GDD = (maximum temperature + minimum temperature)/2-10 °C.

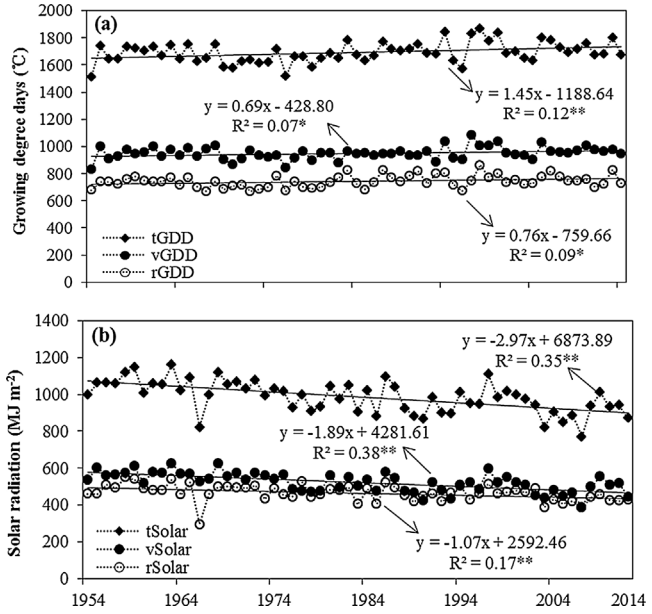

Fig. 1. Annual change of growing degree days (a, °C) and solar radiation (b, MJ m^{-2}) in the whole (a tGDD and b tSolar), vegetative (a vGDD and b vSolar), and reproductive growing periods (○, rGDD and rSolar) of summer maize in 1954–2014 in the experimental station. The sowing date was set to June 16; growing periods were simulated by Hybrid-Maize Model. * significant at $P < 0.05$ and ** $P < 0.01$, respectively.

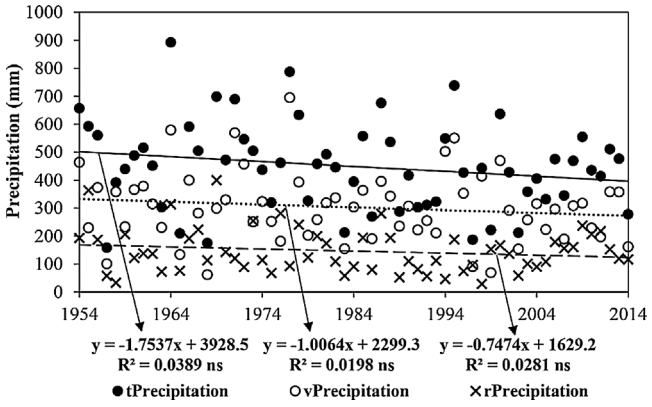

Fig. 2. Annual change of precipitation (mm) in the whole (tPrecipation), vegetative (vPrecipitation), and reproductive growing periods (rPrecipitation) of summer maize in 1954–2014 at the experimental station. The sowing date was set to June 16; growing periods were simulated by Hybrid-Maize Model. ns not significant at P < 0.0.

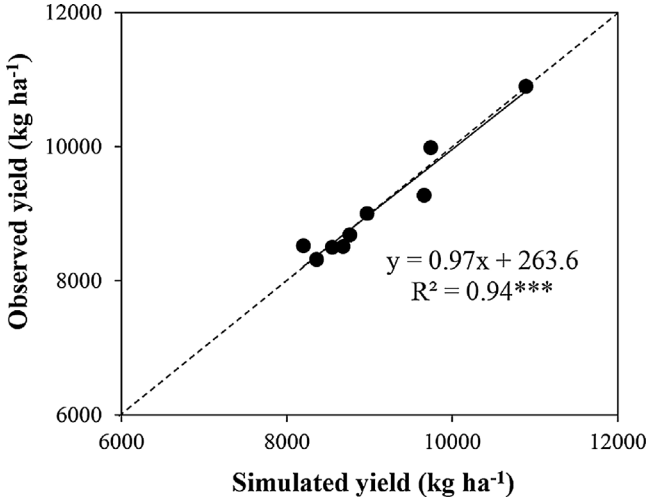

Fig. 3. Simulated yield and observed yield of three hybrids at three different plant densities (n = 9). *** significant at $P < 0.001$; dotted line: diagonal line.

about 25 days more than CF008 and ZD958 to reach the highest light interception rate. At the ear layer, light interception of CF008 was higher at 60 DAS than that of ZD958 and JH5, but decreased to the lowest level at 85 DAS. The light interception at ear layer was very similar between CF008 and JH5, and the values reduced slightly during the period from 60 to 85 DAS.

Leaf net photosynthesis rate (Pn) of all the cultivars used decreased in the period from silking to mid grain filling stage (Fig. 7). Cultivar CF008 had a significantly higher Pn value than ZD958 and JH5 in the first leaf above the ear, but had lower Pn values in other leaves, especially in the ear leaf. Cultivar ZD958 had the highest Pn value in the ear leaf at silking stage, but the Pn values decreased to a lower level at mid grain filling stage.

Compared to ZD958 and FC008, dry matter accumulation (DW) per plant of LG cultivar JH5 was at the highest level especially in the period from silking to maturity (Fig. 8a). In contrast, cultivar ZD958 accumulated significantly greater population DW (kg ha^{-1}) than FC008 and JH5 in the growing period from mid filling stage to maturity at the optimal plant densities. And the population DW was very close between FC008 and JH5 in the whole growing period (Fig. 8b).

DW translocation of populations grown at the optimal plant densities was not significantly different between cultivars, even though the values of ZD958 and CF008 were greater (2733 vs 2678 kg ha^{-1}) than JH5 (2450 kg ha^{-1}) (Fig. 9). However, the contribution of DW translocation to grain yield of CF008 (32.7%) was significantly higher than that of ZD958 (27.9%) and JH5 (27.4%).

The grain yield decreased with the further increase in the plant

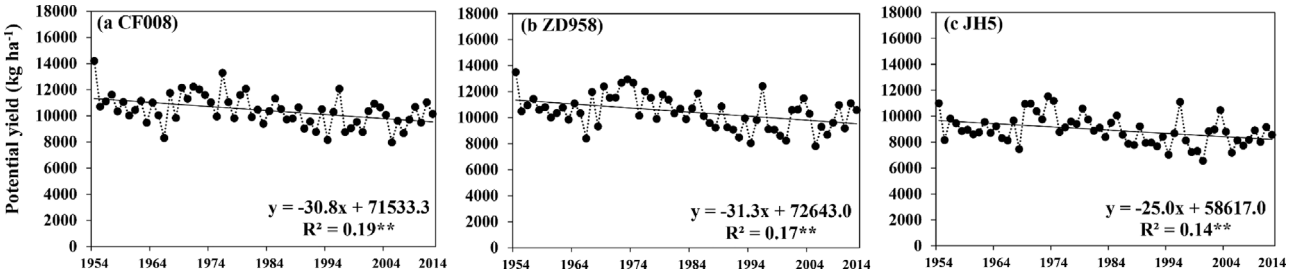

Fig. 4. Simulated potential yield of maize cultivar CF008 with a short growing period (a), medium growing cultivar ZD958 (b), and long growing cultivar JH5 (c) at the optimal plant densities; the optimal density of CF008, ZD958, and JH5 was 97500, 82500, and 67500 plant ha^{-1} in this study, respectively. ** significant at $P < 0.01$.

density as plant density reached the optimal level as a result of decreased kernel number ear^{-1} and decreased 1000-kernel weight (Table 3), especially for cultivars ZD958 and JH5. Correspondingly, the decreased yield was 288, 2332, and 1324 kg ha^{-1} for CF008, ZD958, and JH5, respectively. Harvest index decreased from 0.48 at 97500 plant ha^{-1} to 0.44 at 127500 plant ha^{-1} for CF008, from 0.52 at 82500 plant ha^{-1} to 0.41 at 112500 plant ha^{-1} for ZD958, and from 0.54 at 67500 plant ha^{-1} to 0.41 at 97500 plant ha^{-1} for JH5.

4. Discussion

4.1. Climate change in the North China Plain (NCP)

The climate trend over the past six decades at the experimental site was consistent with previous studies conducted at other regions of the North China Plain (NCP) (Chen et al., 2010; Wang et al., 2012; Zhang et al., 2015). The magnitudes of climate changes were dependent on the regions and time periods. The annual temperature increased by 0.4 °C decade^{-1} in the time period from 1961 to 2008 (Wang et al., 2012) and by 0.6 °C decade^{-1} in 1981–2011 (Zhang et al., 2015) in the northern NCP. In the middle and southern NCP, the temperature increase was 0.16-0.17 °C decade^{-1} in 1961–2008 (Wang et al., 2012). These evidences indicated that warming is becoming faster with time and with the north-toward latitude in the NCP. Annual total solar radiation decreased by 29.1 MJ m^{-2} decade^{-1} in 1961–2003 at the northern NCP (Chen et al., 2010), by 20.9 MJ m^{-2} per decade at the middle of NCP, and by 5.7 MJ m^{-2} per decade at southern NCP (Chen et al., 2010), showing a change similar with temperature. The annual precipitation has been decreasing since 1960s at different sites across the NCP but with large inter-annual fluctuations. The inter-annual change of precipitation indicated that precipitation might be the most important factor limiting maize growth and yield production in certain years in the NCP, especially in the context of constantly decreased groundwater (Liu et al., 2001; Kendy et al., 2004; Chen et al., 2010). On the other hand, an irrigation is necessary shortly after sowing of maize to keep a uniform emergence and growth of maize seedlings in the double cropping system of winter wheat and summer maize in the NCP. However, the decreased groundwater storage might be unable to meet irrigation requirement at maize seedling stage, suggesting that sowing of maize might be delayed until the first effective rainfall after harvest of winter wheat. Moreover, chilling in the early October can block the grain filling of maize in the double cropping system in the NCP (Sun et al., 2007). With the water deficiency and cold stress in mind, the growing period of maize in the NCP would be further reduced, which can result in more negative effects on maize yield.

4.2. Yield response of maize to changing climate in the NCP

The reduced maize yield by climate changes was mainly attributed to the increased temperature, reduced solar radiation and reduced precipitation (Chen et al., 2010; Xiao and Tao, 2016; Xiao et al., 2016). Growing period of maize shortened by the rising temperature is an important contributor to the reduced maize yield (Liu et al., 2010; Tao et al., 2014; Rose et al., 2016). In the present study, the decline trend in the length of reproductive phase of maize over the past 60 years was significant in two out of three cultivars used. Xiao et al. (2016) found that warming could result in a greater advance in maturity than in flowering of maize in the double cropping system of summer maize and winter wheat, thus leading to a shorter reproductive phase in maize. In this context, early sowing or late harvesting was suggested, especially to extend reproductive growing period of maize, which was considered a strategy to compensate negative effects of climatic change (Tao et al., 2014; Waongo et al., 2015; Zhao et al., 2015).

Compared to the rising temperature, the decline in solar radiation was more significant (Fig. 1), which is supposed to account more for the reduced yield of maize over the past 60 years. Xiao and Tao (2016) indicated that a decline in solar radiation reduced maize yield by up to 24% in 1981–2009 in the NCP, while the rising temperature reduced maize yield by around 9%. The decreasing solar radiation was a function of either the shortened growing period (Chen et al., 2010) or

Table 2
Average growing period, solar use efficiency, GDD use efficiency, and their trends per decade (Trend/dec.) during vegetative, reproductive, and total growing season from 1954 to 2014 of maize cultivar CF008 with a short growing period (a), medium growing cultivar ZD958 (b), and long growing cultivar JH5 (c) in North China Plain. * significant at $P < 0.05$, ** $P < 0.01$, and ns not significant at $P < 0.05$. Growing period, solar, and GDD were simulated with Hybrid-Maize, and the sowing date was set to June 16th.

Items		CF008		ZD958		JH5	
		Average	Trend/dec.	Average	Trend/dec.	Average	Trend/dec.
Growing period	vPeriod (days)	47.9	−1.1 ns	48.6	−1.6 ns	51.2	−2.1 ns
	rPeriod (days)	58.9	−0.8 ns	64.4	−1.3*	68.2	−1.8*
	tPeriod (days)	106.9	−1.9 ns	113.0	−2.9*	119.4	−3.9*
Solar	Yield/vSoalr (kg ha^{-1} MJ^{-1})	23.5	0.4 ns	26.7	0.5*	22.8	0.4 ns
	Yield/rSoalr (kg ha^{-1} MJ^{-1})	22.2	0.3**	24.1	0.4**	21.0	0.5**
	Yield/tSolar (kg ha^{-1} MJ^{-1})	11.3	0.2**	12.6	0.2**	10.9	0.2**
GDD	Yield/vGDD (kg ha^{-1} °C^{-1})	12.8	−0.3**	14.6	−0.4**	12.4	−0.3*
	Yield/rGDD (kg ha^{-1} °C^{-1})	13.0	−0.3**	14.5	−0.4**	13.1	−0.3*
	Yield/tGDD (kg ha^{-1} °C^{-1})	6.4	−0.2**	7.3	−0.2**	6.4	−0.1*

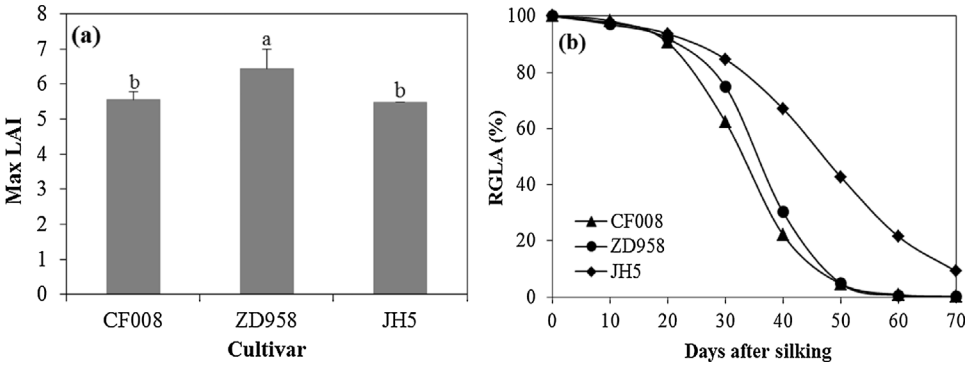

Fig. 5. Maximum leaf area index (***a***, max LAI) at silking stage and relative green leaf area (***b***, RGLA, %) to max LAI during days after silking (DAS) of maize cultivar CF008 with a short growing period (a), medium growing cultivar ZD958 (b), and long growing cultivar JH5 (c) at optimal plant densities in North China Plain. The optimal density of CF008, ZD958, and JH5 was 97500, 82500, and 67500 plant ha^{-1} in this study, respectively. Different letters on the columns indicate significant difference at $P < 0.05$. RGLA was simulated with $y = ae^{b-cx}/(1 + e^{b-cx})$; *a* was set to 1 for three cultivars; b = 5.61, c = 0.18 for CF008; b = 7.76, c = 0.22 for ZD958; b = 4.61, c = 0.10 for JH5. These parameters were derived from LAI observation in 2007. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

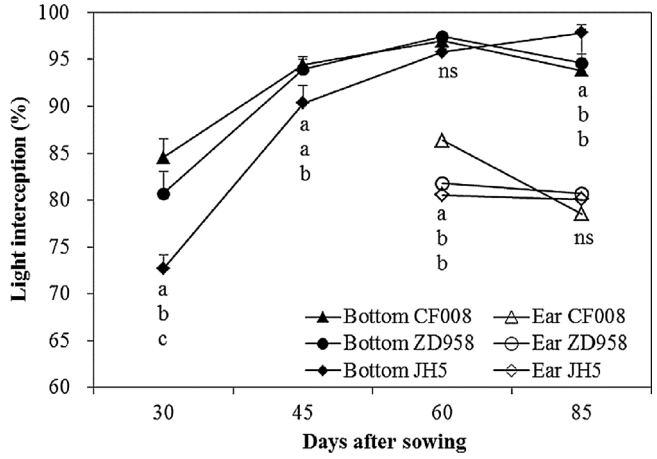

Fig. 6. Population light interception at bottom and ear layers of three maize hybrids with growing period after sowing. CF008, ZD958, and JH5 are short, medium, and long growing cultivars, respectively; values with the same letter were not significant at $P < 0.05$; comparison between cultivars only within the same measurement time; ns not significant at $P < 0.05$.

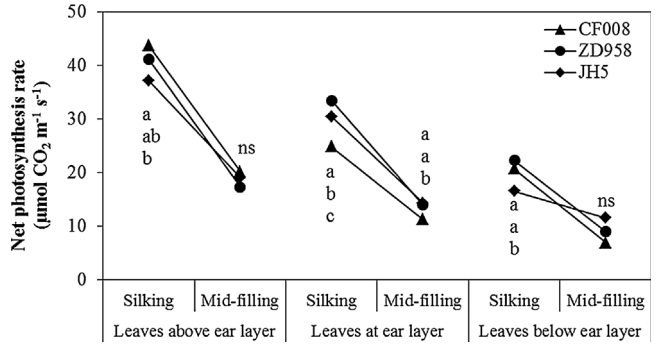

Fig. 7. Net photosynthesis rate (Pn) at different leaf layers of three maize hybrids at silking and mid grain filling stages; CF008, ZD958, and JH5 are small, medium, and long growing cultivars, respectively; three leaves were measured, the first leaf below ear, ear leaf, and the first leaf above ear; values with the same letter were not significant at $P < 0.05$; comparison between cultivars only within the same measurement time; ns not significant at $P < 0.05$.

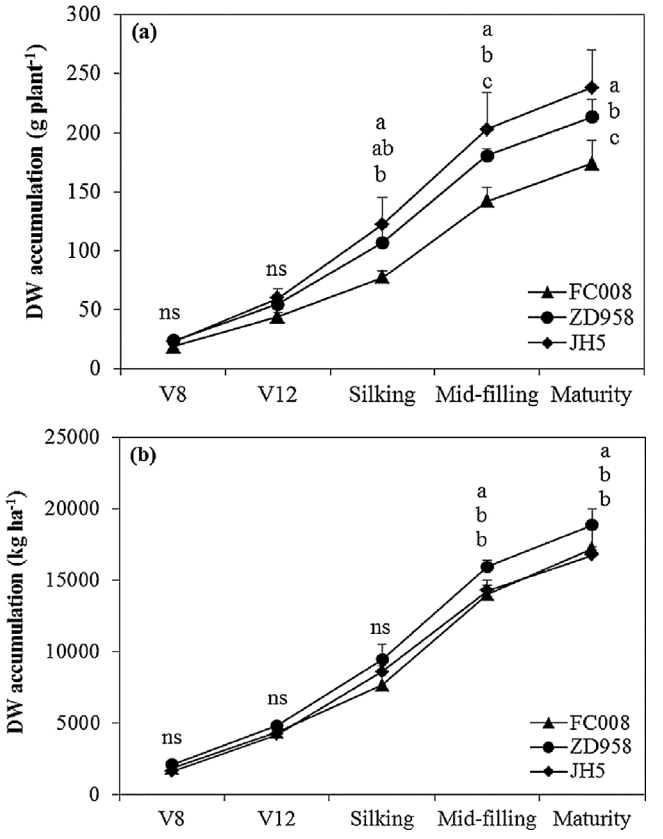

Fig. 8. Plant dry matter (DW) accumulation of single plant (**a**) and plants population (**b**) of three maize hybrids at optimal plant densities. CF008, ZD958, and JH5 are small, medium, and long growing cultivars, respectively. * significant at $P < 0.05$ and ** $P < 0.01$; comparison between cultivars within the same measurement time only; V8 and V12 represent 8-leaf and 12-leaf stages.

increased air pollution (Qian et al., 2006). In particular, Cloudy and drizzly weather condition frequently coincided with the flowering time of maize at the experimental site (Xu et al., 2013). The limited solar radiation during flowering could reduce kernel number and kernel development of maize (Andrade and Vega, 2000).

Maize cultivar with a longer growing period was considered another strategy to offset the negative effects of warming climate on maize yield (Liu et al., 2013; Zhao et al., 2015; Xiao et al., 2016). The compensation effects of longer growing maize cultivar were partly verified in the present study. For instance, the decline in grain yield by climate changes was smallest for cultivar JH5, compared to that of CF008 and ZD958 (Fig. 4). However, grain yield of cultivar JH5 was not expected at the optimal plant density (Table 3), probably as a result of small LAI values (Fig. 5a), small leaf net photosynthesis (Fig. 7), and low dry matter accumulation and translocation (Fig. 8). Moreover, more findings indicated that later-senescing maize cultivars remobilized N from leaves to the ears less efficiently than earlier-senescing cultivars, thus leading to a lower yield (Kosgey et al., 2013; Acciaresi et al., 2014; Swanckaert et al., 2016). Improvements in plant structure and physiology of later-senescing maize cultivar are likely needed if maize cultivars with a longer growing period were used to offset the changing climate.

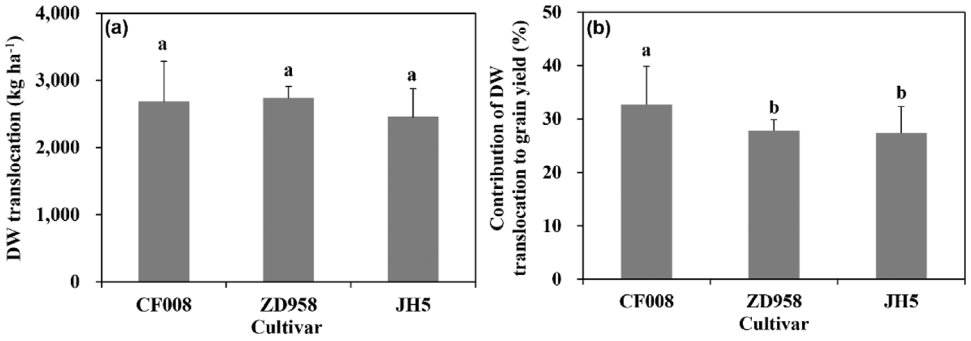

Fig. 9. Dry matter (DW) translocation (**a**) of three maize hybrids and its contribution to grain yield (**b**). CF008, ZD958, and JH5 are small, medium, and long growing cultivars, respectively. DW translocation = dry matter at silking – dry matter in the stove at maturity; contribution of DW translocation = DW translocation/grain yield. Values with same letters are not significant at $P < 0.05$; bars: standard error of mean.

Table 3
Yield characteristics of three maize hybrids with contrasting growing periods at different plant densities. CF008, ZD958, and JH5 are small, medium, and long growing cultivars, respectively. △: the trend of yield characteristics between optimal density (the lowest density) and highest density of each cultivar; values followed with the same letters in each column are not significant at $P < 0.05$; HI, harvest index.

	Density	Yield	Ear number	kernel number	1000-kernel	HI
	(10^4 plant ha^{-1})	(kg ha^{-1})	(ha^{-1})	(ear^{-1})	weight (g)	(%)
CF008	9.75	8132 bc	93519 c	363 cde	240 b	0.48 abc
	11.25	7689 c	104162 b	330 fg	234 b	0.43 c
	12.75	7845 c	110185 a	302 g	237 b	0.44 bc
	△	*−288*	*16667*	*−61*	*−3*	*−0.04*
ZD958	8.25	9846 a	83796 d	453 b	262 a	0.52 ab
	9.75	8378 bc	94908 c	376 cd	238 b	0.42 c
	11.25	7514 c	96296 c	336 ef	235 b	0.41 c
	△	*−2332*	*12500*	*−116*	*−27*	*−0.12*
JH5	6.75	9021 ab	69445 e	493 a	262 a	0.54 a
	8.25	7677 c	80556 d	392 c	242 b	0.44 bc
	9.75	7697 c	93056 c	350 def	238 b	0.41 c
	△	*−1324*	*23611*	*−143*	*−23*	*−0.13*

Increasing population density of plant has been widely adopted to improve maize yield thanks to the increased plant density tolerance of new maize cultivars (Tokatlidis and Koutroubas, 2004; Hammer et al., 2009). Short and erect leaves in the upper canopy layer are favored at high plant densities (Ma et al., 2014), which is referred to as a small plant size. According to the optimal plant density of three maize cultivars used in the present study, plant density tolerance of cultivar JH5 is much lower than that of cultivars CF008 and ZD958. The length of growing period is supposed to depend on the plant size, which was confirmed at least in the present study; the larger the plant size, the longer the growing period (Table 2). Studies focusing on both growing period and plant size in maize were not found. However, Antonietta et al. (2014) reported that later-senescing maize cultivars in Argentina did not yield better at high plant densities, consistent with findings of Kosgey et al. (2013) in New Zealand. It is supposed that delayed senescence in the low canopy leaves of later-senescing maize cultivars could increase energy consumption by maintaining a high respiration in the late growing period (Antonietta et al., 2014). A long-lasting intra-plant competition of later-senescing cultivars likely reduced the tolerance of high plant density (Acciaresi et al., 2014). The relationship between growing period, population competition, and plant density tolerance is still unclear, which should be concerned in the future study.

In the perspective of grain yield, cultivar CF008 and JH5 apparently were not the optimum option in the NCP at least in the past 60 years. By contrast, yield of medium growing cultivar ZD958 was estimated to remain at the highest level in 1954–2015 (Fig. 4). The medium tolerance of high plant density, along with a medium growing season might be able to improve maize yield further in the NCP even under changing climate. Maize plant architecture and growing period are supposed to be both taken into account to adapt to the changing climate. For instance, plant architecture of ZD958 can distribute solar radiation more uniform in the canopy (Fig. 6), which probably can explain the high yield. Upright and shorter leaves in the upper canopy layer is becoming favored with genetic improvement in maize (Ma et al., 2014). With this in mind, increasing plant density tolerance of long growing maize cultivars by improving plant architecture is supposed to be a better option to increase yield as well as to adapt changing climate.

5. Conclusion

This study confirmed that maize cultivars with a long growing period can retard the yield decline caused by climate changes in the North China Plain. In the double cropping system of winter wheat and summer maize, yield of medium growing maize cultivars was, is, and will be at the highest level in a short future due to the high plant density tolerance. Maize cultivars with a longer growing period is supposed to adapt to the changing climate better. But strategies focusing on extending growing period of maize cannot completely offset the negative effects of climate change due to the reduced tolerance of plant density. Improvement of plant architecture in space and time should be taken into account to resolve the conflict between adapting climate change and increasing plant density in maize.

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